BIOTRICKLING FILTERS FOR AIR POLLUTION CONTROL

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INTRODUCTION

Biological treatment of contaminated air is an emerging technology for air pollution control. The principle is relatively simple: a contaminated air stream is passed through a porous packed bed on which pollutant-degrading cultures are immobilized. Like all biological treatment processes, air biotreatment relies on microbial reactions for the degradation of waste compounds. Bioreactors for air pollution control have found most of their success in the treatment of dilute, high flow waste gas streams containing odors or volatile organic compounds (VOCs). Under optimal conditions, the volatile or gaseous pollutants can be degraded completely to carbon dioxide, water and excess biomass. In the case of contaminants such as H_2S or reduced sulfur compounds, or biodegradable chlorinated compounds, harmless sulfate or chloride are additional by-products. Bioreactors for air pollution control hold promise to treat many contaminants in a wide spectrum of applications. The technology has a niche in commercial and industrial applications where high air flows and low pollutant concentrations are encountered (Figure 1). It offers several advantages over traditional technologies such as incineration or adsorption. These include lower treatment costs, reduced environmental impact, absence of formation of by-products such as nitrogen oxides (NOx) or spent activated carbon, low energy demand, no need for fossil fuel burning, and low temperature treatment.

The two most promising bioreactors for air pollution control are biofilters and biotrickling filters. Biofiltration has been recently reviewed (1); hence this article is only concerned with biotrickling filters.

Biofilters work by passing a humid stream of contaminated air through a damp packing material, usually compost mixed with wood chips or any other bulking agent, on which pollutant degrading bacteria are naturally immobilized. Biofilters are simple and cost effective. They require low maintenance and are particularly effective for the treatment of odor and volatile compounds that are easy to biodegrade and for compounds that do not generate acidic by-products. Biofilters are increasingly used in industrial applications.

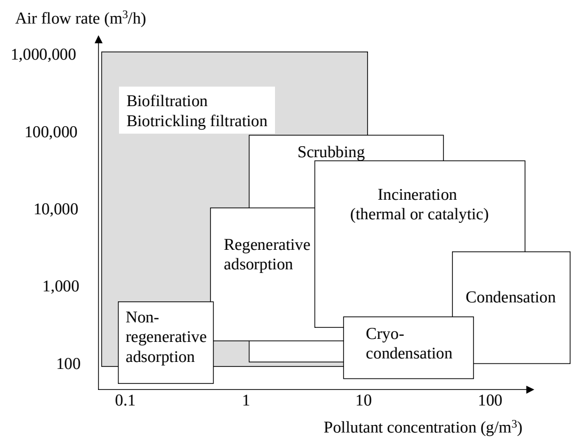

Figure 1. Applicability of various air pollution control technologies based on air flow rates and concentrations to be treated (updated from reference 2).

- **Biotrickling filters** work in a similar manner to biofilters, except that an aqueous phase is trickled over the packed bed, and that the packing is usually made of some synthetic or inert material, like plastic rings, open pore foam, lava rock, etc. The trickling solution contains essential inorganic nutrients such as nitrogen, phosphorous, potassium, etc. and is usually recycled. Biotrickling filters are more complex than biofilters but are usually more effective, especially for the treatment of compounds that generate acidic by-products, such as H_2S. They can be built taller than biofilters. Biotrickling filters are more recent than biofilters, and have not yet been fully deployed in industrial applications.

BIOTRICKLING FILTRATION PRINCIPLE

The principle of biotrickling filtration is schematically explained in Figures 2 and 3 while typical characteristics of biotrickling filters are listed in Table 1. Biotrickling filters are biological scrubbers. At a first glance, the mechanisms appear to be relatively simple: contaminated air is contacted with an immobilized culture of pollutant degrading organisms in a packed bed. A more detailed examination of the processes involved (Figure 3) reveals that elimination of the pollutant is the result of a combination of physico-chemical and biological phenomena. Understanding these phenomena is a key to the successful deployment of the technology.

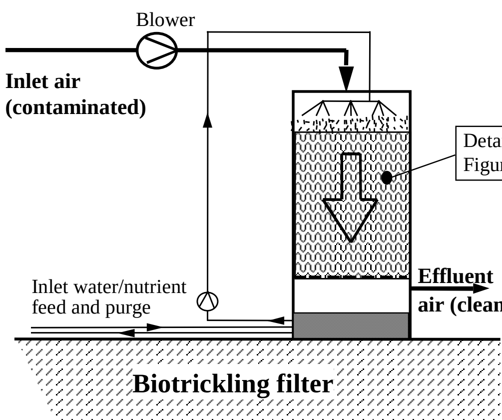

Figure 2. Schematic principle of biotrickling filtration; here cocurrent operation is shown.

In biotrickling filters, contaminated air is forced through a packed bed, either downflow or upflow. The packed bed is generally made of an inert material such as a random dump or a structured plastic packing, or less often, an open pore synthetic foam or lava rocks. The packing provides the necessary surface for biofilm attachment and for gas-liquid contact. During treatment, an aqueous phase is recycled over the packing. It provides moisture, mineral nutrients to the process culture and a means to control the pH or other operating parameters. The system is continuously supplied with essential mineral nutrients such as nitrogen, phosphorus, potassium, and trace elements via a liquid feed. In general, most of the pollutant is biodegraded in the biofilm, but part may also be removed by suspended microorganisms in the recycle liquid (3). Possible biodegradation metabolites will leave the system via the liquid purge along with small amounts of biomass. Usually, less than 10% of the carbon-pollutant entering the system leaves via the purge (3).

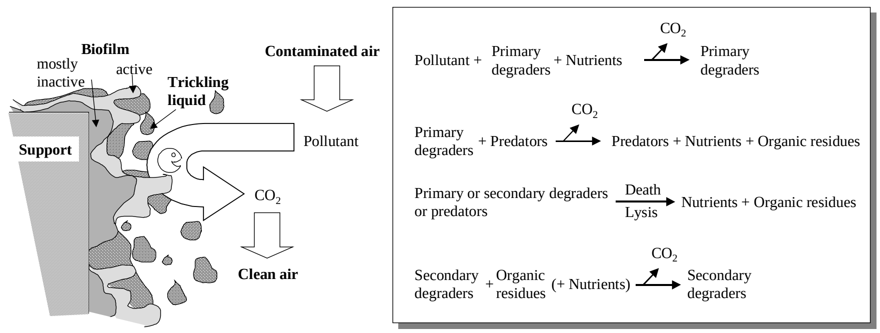

Figure 3. Mechanism of pollutant removal and main biological processes involved in biotrickling filters.

Biotrickling filters work because of the action of the pollutant degrading microorganisms. In the case of the removal of hydrocarbon vapors, the primary degraders are aerobic heterotrophic organisms that use the pollutant as a source of carbon and energy. For H_2S or ammonia removal, the primary degraders are autotrophes, and will use the pollutant as a source of energy, and carbon dioxide as source of carbon for growth. The removal of compounds such as dimethyl sulfide or dimethyl disulfide will require both autotrophes and heterotrophes to be present. In any case, the biotrickling filter will host a wide variety of microorganisms, similar to those encountered in waste water treatment operations. The microorganisms responsible for pollutant removal in biotrickling filters are usually aerobic because biotrickling filters are well aerated systems. However, it has been proposed that the deeper parts of the biofilm (see Figure 3), where anaerobic conditions probably prevail, can be utilized to perform anaerobic biodegradation (e.g., reductive dechlorination, or NO_x reduction) for the treatment of pollutants that are otherwise recalcitrant under aerobic conditions (4). Anaerobic treatment in aerobic biotrickling filters is still an experimental area.

Table 1. Typical characteristics of biotrickling filters.

Biotrickling filter bed height	1-5 m
Biotrickling filter cross section area	1-3,000 m^2
Air flow treated	100-1,000,000 m^3 h^{-1}
Packing void volume[a] -Plastic rings, foam, random or structured packing -Lava rock	 90-95% ~50%
Empty bed gas retention time[b]	2-60 s
Pressure drop	< 1 cm of water column per m bed depth
Operating temperatures	15-50 °C
Trickling rates[c]	0.01-10 m h^{-1}
Liquid dilution rate[d]	0.1-2 day^{-1}
Usual pH of the recycle liquid -removal of VOCs or compounds difficult to degrade -removal of H_2S	 ~7 1-2
Inorganic nutrient supply (N, P, K, traces)	Usually 0.05 to 1 times the amount calculated using biodegradation stoichiometry
Inlet pollutant concentration -VOCs -Odors	 0.01-10 g m^{-3} 500-50,000 odor units
Typical pollutant removal efficiencies	60-99.9+%

[a] Value at reactor startup; over time, biomass growth will decrease bed porosity, typically by 10-30%
[b] The empty bed gas retention time (EBRT) is defined as the bed volume / air flow
[c] Trickling flow rate / bed cross section area
[d] Liquid feed rate / recycle liquid volume

As illustrated in Figure 3, a major fraction of the biofilm becomes inactive (mostly because of mass transfer limitations) as the biofilm grows, and active primary degraders only constitute a minor fraction of the total population in the biofilm. Secondary degraders feeding on either metabolites, biopolymers, or predators feeding on the primary degraders include bacteria, fungi, and higher organisms such as protozoa, rotifers, even mosquito or fly larvae, worms or small snails. The importance of higher organisms for the overall process should not be underestimated. They have been shown to play an important role in reducing the rate of biomass accumulation and in recycling essential inorganic nutrients (5, 6). As a matter of fact, comparison of traditional mineral growth media with biotrickling filter recycle liquid composition reveals that most biotrickling filters are operated under various degrees of inorganic nutrient limitation. The relationship between nutrient supply and biomass growth is discussed further in this chapter.

BIOTRICKLING FILTER PERFORMANCE

Definitions and Factors Affecting Performance

Operation and performance of biological reactors for air pollution control is generally reported in terms of removal efficiency, or pollutant elimination capacity as a function of the pollutant loading, or the gas empty bed retention time (EBRT). These terms are defined in Equations 1-4.

$$\text{Removal} = \text{RE} = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \quad (\%) \qquad (1)$$

$$\text{Pollutant Elimination Capacity} = \text{EC} = \frac{(C_{in} - C_{out})}{V} \times Q \quad (\text{g m}^{-3}\ \text{h}^{-1}) \qquad (2)$$

$$\text{Empty Bed Retention Time} = \text{EBRT} = \frac{V}{Q} \quad (\text{s or min}) \qquad (3)$$

$$\text{Pollutant loading} = \text{L} = \frac{C_{in}}{V} \times Q \quad (\text{g m}^{-3}\ \text{h}^{-1}) \qquad (4)$$

where C_{in} and C_{out} are the inlet and outlet pollutant concentrations (usually in g m^{-3}), respectively, V is the volume of the packed bed (m^3) and Q is the air flow rate (m^3 h^{-1}). Pollutant concentrations are usually reported as mass per volume; conversion of volumetric to mass concentrations is done using the ideal gas law which reduces to Equation 5 at room temperature.

$$\text{Concentration (g m}^{-3}) = \frac{\text{Concentration (ppm}_v) \times \text{molecular weight of pollutant (g mol}^{-1})}{24{,}776} \qquad (5)$$

It should be stressed that the elimination capacity and the loading are calculated using the volume of the packed bed and not to the total volume of the reactor. Depending on the reactor design, the volume of the packed bed volume will be about 40-90% of the total reactor volume. Also, the

EBRT is calculated on the basis of the total volume of packed bed (Equation 3). The actual gas residence time will be lower depending on the porosity of the packing, the dynamic liquid hold-up and the amount of biomass attached to the packing. The porosity of packing ranges from about 50% (lava rock) to 95% (all random or structured packings), the liquid holdup is usually less than 5% of the bed volume, and biomass may occupy 5% to 30% of the bed volume. Hence, the actual gas residence can be less than half the EBRT.

A typical elimination capacity vs. pollutant loading curve is shown in Figure 4. It is usual to report the performance as a function of the load, i.e., inlet concentration × air flow, rather than the concentration. This enables comparison of systems of different sizes operated under different conditions. One underlying assumption is that the performance depends only on the pollutant load, hence, that low concentrations-high flowrates conditions lead to similar elimination capacities as high concentrations-low flowrates. This assumption is generally valid because the pollutant concentrations commonly encountered in biotrickling filters are high enough for the micro-kinetics to be of zero order. This is no longer true at very low pollutant concentrations (typically below 0.05 - 0.1 g m^{-3}), in particular for pollutants with high Henry's law coefficients, because first order kinetics will prevail in the biofilm resulting in a reduction of the maximum elimination capacity.

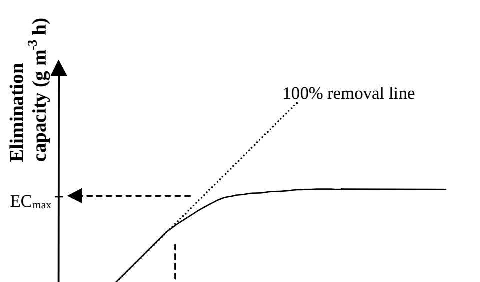

Figure 4. Schematic of a typical elimination capacity vs. load characteristic for a biotrickling filter.

Examination of Figure 4 reveals that there are essentially three operating regimes.

1. Low loading, also called first order regime. The elimination capacity and the loading are identical and the pollutant is completely removed. The biotrickling filter is operated well below its maximum elimination capacity. The performance increases proportionally with the loading.
2. Intermediate range. Breakthrough of the pollutant occurs. With higher inlet concentration or higher air flow rates, the elimination capacity increases, but to a lesser extent than the loading.
3. High loading, also called zero order regime. The biotrickling filter is operated at its maximum elimination capacity. Increases in pollutant concentration or of the air flow rate do not result in further increases in elimination capacity, the removal efficiency decreases.

For the evaluation of biotrickling filter performance, one should consider both the maximum elimination capacity and the removal efficiency. For practical reasons, academic research is mainly concerned with the maximum elimination capacity or with high performance, which occur at relatively high pollutant concentration and often less than ~90% removal efficiency. On the other hand, reactor design for industrial application often needs to meet a certain discharge requirement, or achieve a high removal percentage. Thus there might be some challenges in extrapolating research data for reactor design. In this context, the critical load defined as the maximum loading before the removal deviates significantly from the 100% removal line (Figure 4) is a valuable parameter. But there are limitations to the use of the critical loading. It is relatively sensitive to the pollutant inlet concentration, thus extrapolation of low flow-high concentrations to high flow low-concentration should be avoided.

Examples of Biotrickling Filter Performance

Research over the past ten years has greatly broadened the range of pollutants that can be treated in biotrickling filters, including volatile organic compounds (VOCs), chlorinated hydrocarbons, reduced sulfur compounds, and compounds containing nitrogen. Typical examples are presented in Table 2.

Maximum elimination capacities generally are in the range of 5-200 g m^{-3} h^{-1}. Although many factors influence performance, a few general comments can be made. As biotrickling filters rely on microorganisms as the catalysts for pollutant conversion, biodegradability of the pollutant is of prime importance. Decreasing

Table 2. Laboratory studies on removal of different pollutants in biotrickling filters.

	Methanol (7)	MTBE (8)	Hexane (9)[c]	Dichloromethane (10)	H_2S (11)	Nitrobenzene (12)
Compound classification						
Biodegradability	High	Low	Intermediate	High	High	Low
Water solubility	High	High	Low	Intermediate	Intermediate	Intermediate
Substrate profile	VOC; carbon and energy source	VOC; carbon and energy source	VOC; carbon and energy source	Cl-compound; carbon and energy source	Inorganic; energy source	N-compound; carbon and energy source
Operation						
Packing	NOR-PAC polypropylene packing	Lava rock / polypropylene Pall rings	Foam	Ceramic saddles	Foam packing	Perlite
Mode of operation	N/A	Cocurrent	Cocurrent/intermittent trickling	Cocurrent	Countercurrent	Cocurrent
Source of microorganisms	Activated sludge	Adapted microbial consortium	Two pure bacterial species	*Hyphomicrobium* sp. GJ21	NA	Adapted microbial consortium
Performance						
Start-up	5 days	7 months	50 days	7 days	2 weeks	4 weeks
EC_{max} ($g\ m^{-3}\ h^{-1}$)	100	42-50	7.5	150	100	50
Critical load ($g\ m^{-3}\ h^{-1}$)	~80	~40	~5	NA	~70	NA
- EBRT (s)	69	39-90	288		NA	
- Inlet concentration ($g\ m^{-3}$)	1.5	0.4-1	0.4		0.4-1.4	

biodegradability causes lower elimination capacities and/or longer periods of adaptation. The use of specially acclimated or enriched microorganisms may be considered in these cases. Equally important is the accessibility of the pollutant to the microorganisms. The overall rate of pollutant removal may be limited by mass transfer rate of the pollutant into the biofilm, which depends mainly on the pollutant's air-water partition which is in turn best described by the Henry coefficient. Mass transfer limitation leads to a biofilm not completely saturated with the pollutant, hence pollutant concentrations in the biofilm are below those required for maximum biological activity. Means to improve the overall mass transfer rate in biotrickling filters include the selection of packing materials with a high specific surface area and intermittent trickling to reduce the thickness of the water film on the biofilm (Fig. 3).

As illustrated in Table 2, many different types of packing materials have been used in biotrickling filters, and research in this area is still ongoing. The packing should combine a high porosity to minimize the pressure drop across the reactor and a high specific surface area to maximize biofilm attachment and pollutant mass transfer. Other factors to consider for a packing include water holding capacity, structural strength, surface properties, weight, stability over time, and cost.

Reaction conditions in the biotrickling filter can be optimized by controlling the pH, the concentrations of nutrients and metabolic end-products in the recycle liquid. Many biotrickling filters are equipped with a pH control, and with automatic water/nutrient addition to control ionic strength. The optimum pH depends on the process culture. Most VOC-removing biotrickling filters are operated at a near neutral pH. On the other hand, H_2S oxidizing microorganisms such as *Thiobacillus sp.* are acidophilic and show maximum activity at low pH. pH values as low as 1-2 are not uncommon in biotrickling filters treating H_2S vapors. Treatment of sulfur and chlorinated compounds will result in the accumulation of sulfate and chloride in the recycle liquid, respectively. These salts will inhibit biodegradation if certain concentrations are exceeded, and frequent supply of fresh water and purge of the recycle liquid is required to prevent accumulation of inhibitory concentrations. The dilution rate can be controlled by continuous measurement of the conductivity of the recycle liquid or by using ion selective electrodes.

BIOMASS GROWTH IN BIOTRICKLING FILTERS

Growth Kinetics

Clogging of biotrickling filters by growing biomass is one factor that has markedly slowed down the implementation of biotrickling filters at the industrial scale. A better understanding of biomass growth in biotrickling filters is warranted. In general, pollutants are used by the primary degraders to produce new biomass and to generate energy for maintenance (see Figure 3). These processes have been extensively investigated in batch or continuous monocultures. The situation is much more complicated in biotrickling filters where a complex ecosystem exist. In a first approximation, neglecting heterogeneities and mass transfer effects, one can write that the rate of pollutant degradation depends on the intrinsic growth rate of the active fraction of the primary degraders (X_1) and their maintenance requirement, as in Equation 6.

$$EC = \left(\frac{\mu}{Y_{X/S}} + m \right) \times X_{1(\text{active fraction})} \qquad (6)$$

where μ is the specific growth rate of the primary degraders, $Y_{X/S}$ is the biomass yield, m the maintenance energy requirement, and $X_{1(\text{active fraction})}$ is the biomass content of active primary degraders per volume of reactor.

The specific growth rate of the active fraction of the primary degraders can be expressed using a modified Monod type equation,

$$\mu = \frac{\mu_{max} \times S}{Ks + S} \times \frac{N}{Ks_N + N} \times \frac{O}{Ks_O + O} \times \frac{I}{1 + \frac{I}{K_I}} \qquad (7)$$

where S is the pollutant and substrate, N is any nutrient, O is the oxygen, and I any inhibitor, and Ks, KsN, KsO, and KI are the respective half-saturation and inhibition constants.

A similar equation can be written for all the species (or group of species) present in the system. Each will have one or several specific substrates, specific kinetic constants, and thus a specific growth rate. The overall rate of biomass accumulation is the sum for all the different species (designated by the indices i) of the growth rate minus death and lysis (d term), the predation by other species and the wash-out via the recycle liquid purge. This is expressed in Eq. 8.

$$\text{Rate of biomass accumulation} = \sum_i \left((\mu_i - d_i) \times X_i - \text{Predation}_i - \text{Wash out}_i \right) \qquad (8)$$

Equations 6-8 are highly simplified since they do not take local heterogeneities into account. Still they define a number of parameters that are impossible to determine. A possible solution is to split the process culture into large classes of organisms, such as primary degraders, secondary degraders, predators, etc. and use lumped kinetic parameters. This is an area of current research. Even so, Eq.s 6-8 reflect the fact that the pollutant elimination and the observed biomass growth are interrelated in a complex manner. The equations further allow development of biomass control strategies for biotrickling filters. This is discussed in the next section.

Strategies for Controlling Biomass Growth

Examination of Equations 6-8 suggests several possible approaches to controlling biomass growth. Attempts can be made to reduce the overall rate of biomass accumulation (Equation 8) by either reducing the specific growth rate or increasing death and lysis. Several means have been investigated. Other options include increasing predation, washing-out or otherwise periodically removing the excess biomass. These are briefly discussed.

The first option to prevent clogging is the reduction of the biomass accumulation rate or of the specific growth rate (Equations 7). The challenge is to reduce biomass accumulation, while maintaining a high pollutant removal rate (Equation 6), since growth and pollutant elimination are often tightly linked. This can be achieved by reducing the biomass yield coefficient ($Y_{X/S}$) and/or increasing the maintenance requirements (m). Growth, biomass yield, death and lysis, activity and maintenance are interrelated parameters reflecting general cell metabolism and as such they are difficult to influence independently.

Table 3 reports various attempts to reduce the specific growth rate in biotrickling filters. These include limiting the supply of nutrients essential for growth (N or K), the use of nitrate as a nitrogen source instead of ammonium, the addition of compounds such as NaCl in concentrations that partially inhibit microbial growth, etc. In general, these strategies also result in reduction of microbial activity, thus they lower reactor performance. Hence, larger reactors will be required to treat the same volume of waste gas, which will increase the capital costs. An interesting option is the use of organisms with lower biomass growth rates and yields such as fungi. Interestingly, under similar conditions, fungi have shown a higher removal rate and a lower biomass accumulation rate than bacteria in toluene-degrading biotrickling filters operated under nutrient-limiting conditions (13).

The second option is to stimulate predation of the process culture by higher organisms such as protozoa (5), possibly even larger organisms such as larvae, small snails or other biomass-eating organisms. This is a promising approach since it will not lead to a reduction of the performance, and will not result in excess biomass to be disposed off, as for the methods discussed in the next paragraph. The challenge is that higher organisms may be

Table 3. Options for reduction of the biomass growth rate in biotrickling filters.

Option	Principle	Reference
Nutrient limitation - Nitrogen - Phosphate - Potassium	Reduction of the biomass yield	 13, 17, 18 19 19
Use of $N\text{-}NO_3^-$ instead of $N\text{-}NH_4^+$	Reduction of the biomass yield	20, 21
Use of specific microbial species	Selection of low biomass yield species	13
Addition of growth inhibitors	Reduction of the specific growth rate	20, 22

difficult to control and/or to maintain in the biotrickling filter. This is an area of development, and advances are expected in the near future.

The last option to prevent clogging is to remove the excess biomass. This is usually done periodically rather than continuously, because shear by the trickling liquid during normal operation is not sufficient to remove substantial amounts of attached biomass (14). Hence, the recycle liquid only contains a low concentration of biomass and increasing blow-down does not wash-out much biomass. When periodical removal of biomass is chosen, the biotrickling filter is best operated at a high elimination capacity, and biomass is allowed to accumulate up to a given point where remedial action is required. From a cost perspective, the capital costs will be lower because a smaller reactor will suffice, but clogging will necessitate frequent cleaning, thus increasing the operating costs (15). Removal of biomass can be done either physically or chemically (Table 4). Physical removal of biomass relies on biofilm detachment by high shear forces. This can be done by backwashing the reactor, or by periodical stirring of the packed bed. Although these techniques result in prolonged, stable biotrickling filter operation, certain drawbacks exist (Table 4). Chemical removal of biomass is a simpler operation as no major changes of the reactor configuration are required. In this procedure, a chemical solution is recycled over the packing using the existing system for liquid recycling. A stable toluene-degrading biotrickling filter was obtained by periodic washing of the packing with a NaOH solution for 3 hours (13). A post-treatment with HCl was needed to restore the pH to a neutral value. Other chemicals such as sodium hypochlorite and hydrogen peroxide may be more effective in removing biomass, but they are also more toxic to the microbial population (16). This could potentially slow down the restart of the reactor.

Table 4. Options for removal of excess biomass in biotrickling filters. Note that all methods were only tested at relatively small scale.

Option	Advantages	Disadvantages
Backwashing ref 21, 23	• Mild treatment • Possibly redistributes packing thus may avoid formation of preferential paths or short circuits	• Requires larger reactors (+40%) for packing fluidization • Requires packing that can be fluidized
Periodical stirring ref 24, 25	• Probably low cost to perform • Easy to automate	• Complicated reactor design and construction • Higher capital costs • Not feasible with all packings
Chemical washing ref 13, 16	• Effective removal of biomass • Does not require reactor modification	• Toxicity to microorganisms • Secondary waste

Unfortunately, all biomass control strategies have only been investigated in the laboratory and no experience is available from industrial-scale biotrickling filters. This is because most full-scale biotrickling filters have been designed for applications with low potential for clogging. In the future, design and operation of biotrickling filters will need to find the optimum between operation of large, low-performance biotrickling filters that do not require biomass removal, and small, high-performance biotrickling filters with high potential for biomass accumulation (15). The perspective for progress in controlling biomass growth in biotrickling filters suggest that the latter option will be preferred.

BIOTRICKLING FILTRATION COSTS

Capital Costs

Capital costs for biotrickling filters vary a great deal with the size of the biotrickling filter and the material of construction. The size of the biotrickling filter is a function of the air flow, the nature and concentration of the pollutant treated and the required removal efficiency. The presence of corrosive gases (e.g., H2S) or solvent vapors will influence the choice of the construction material (polyethylene, fiberglass, steel or concrete). The cost of the biotrickling filter will be further influenced by the presence of dust or fine particles, by excessively high or low temperatures, by highly fluctuating pollutant concentrations, etc. Controls and ducting can also be a significant expense. Hence before reactor design and construction, extended problem definition which includes a detailed characterization of the exhaust air is required.

Deshusses and Cox (15) have recently proposed a simple relationship (Equation 9) to estimate the capital cost of a biotrickling filter based on the volume of the bed. The costs include basic instrumentation (pumps, level switch) but no ducting and are for a simple biotrickling filter constructed out of inexpensive materials. For expensive materials such as stainless steel, a multiplication factor should be used. The cost obtained by Equation 9 is a rough estimation, with ± 20% accuracy.

$$\text{Biotrickling Filter Capital Cost (\$)} = 13{,}000 \times \text{Bed Volume}^{0.757} \quad (9)$$

for bed volumes ranging from 5 to 1000 m^3 where the reactor volume is in m^3. Based on the concentration of the pollutant, the target removal efficiency, and the air flow to be treated, the bed volume can be determined. Equation 9 is then used to estimate the capital cost (Table 5). Of course vendor quotes are more appropriate for a detailed economic evaluation of the final installed costs.

Table 5 Estimated costs, footprint and treatment capacity of biotrickling filters of various sizes.

Bed volume (m^3)	Capital costs (Equation 1) (\$)	Approx.e footprint[a] (m^2)	Approximate air flow that can be treated[b] ($m^3\ h^{-1}$)
5	$45k	1 - 2.5	300 - 3,600
10	$75k	2 - 5	600 - 7,200
20	$125k	4 - 10	1,200 - 14,400
50	$250k	10 - 25	3,000 - 36,000
100	$425k	20 - 50	6,000 - 72,000
200	$720k	40 - 100	12,000 - 144,000
500	$1.4m	100 - 250	30,000 - 360,000
1000	$2.4m	200 - 500	60,000 - 720,000

[a] Estimated using a 2-5 m bed height; to convert to sq. ft multiply by 11. [b]Calculated using EBRT of 5 s. to 1 min.; to convert to cfm, multiply by 0.59.

Operating Costs

The determination of the cost of operating a biotrickling filter should include: 1) nutrients and water expenses, 2) electricity for the blower and the recycle pump and miscellaneous electrical equipment, 3) maintenance, 4) costs associated with controlling the growth of biomass, 5) capital costs (amortization). A detailed discussion of each of these costs is beyond the scope of this chapter. The reader is referred to specialized literature and vendor information for more details (15). Even so, in general the following applies:

- Nutrients, chemicals (e.g., for pH control) and water are usually a relatively small fraction (10-30%) of the total operating costs.
- Electricity for the blower is often a major fraction of the total operating expenses.
- Maintenance of biotrickling filters is minimal. A reasonable estimate is 2-4 hours per week. Most important is to inspect spray nozzles for possible clogging which would result in inadequate bed wetting.
- If the biotrickling filter is likely to experience clogging problems, the costs associated with controlling the growth of biomass must be included. These can be significant (15), up to half of the total operating costs. As discussed in the previous section, various approaches exist to control biomass growth. Unfortunately, there is only limited experience at the industrial scale. Careful evaluation of the various options is recommended.
- Since biotrickling filter operation is relatively inexpensive, capital cost amortization will be significant compared to other costs. An average fraction, assuming a plant life of 10-20 years is between 20 and 40% of the total treatment costs. This stresses the importance of proper sizing and careful selection of the materials to minimize the actual capital costs.

A convenient way to compare the operating costs of biotrickling filters is to report the costs per thousands of cubic meter of air treated, i.e., to divide the yearly costs incurred by the volume of air treated in a year (in thousands of m^3). Usual values for the operating costs range from \$0.05 to \$1.5 per 1000 m^3 of air treated not including capital costs, and from \$0.1 to \$3 per 1000 m^3 when capital amortization is included. The wide range reflects the variety of possible applications and sizes of biotrickling filters. Typically, large biotrickling filters tend to be more economical per unit volume of air treated than small biotrickling filters.

CASE STUDIES

In this Section, four cases of biotrickling filtration are presented. These case studies are reported to the best of our knowledge. Their description in this chapter does not constitute an endorsement of the design or of the vendor. Note also that the methods for calculating the treatment costs may be different from case to case. Hence, treatment costs may not be directly comparable. Nevertheless, they are included for information purposes, as an indication of the potential economic value of the technology.

H_2S and VOC treatment at a Wastewater Treatment Plant in Los Angeles, California

Wastewater treatment plants have to control various odors and VOC emissions. The odor is generally from H_2S and from reduced sulfur compound emissions. Usually, the H_2S concentration is in the 3-100 ppm_v range while reduced sulfur compounds are in the ppb_v to ppm_v range. Some VOCs (aliphatics, aromatics and some chlorinated) are also emitted, usually in the ppb_v range. Biotrickling filters have been proposed as one promising alternative treatment to the present use of chemical scrubbers. A pilot study was conducted in the year 2000 by the University of California, Riverside at the Hyperion Treatment Plant in Los Angeles, to evaluate the efficacy of biotrickling filters for the treatment of contaminated air from the headworks. The Hyperion plant treats domestic and industrial wastewater from the Los Angeles Basin. Odor nuisance and growing concern about the potential toxicity of individual compounds require removal of H_2S as well as VOCs such as benzene and chlorinated compounds such as methylene chloride and chlorobenzenes. The main objective of this feasibility study was to evaluate combined treatment of H_2S and VOCs in a single-stage biotrickling filter. A particular emphasis was placed on determining the effect of pH on the elimination of the trace VOCs. The reactor used for this demonstration is a well instrumented pilot unit (26) which includes two vessels, but only one was used in this project (see Table 6 and Figure 5). The air was in an upflow mode, secondary effluent water (2.2 L $m^{-3}_{reactor}$ h^{-1}) was used as a nutrient source for microbial growth and to wash out sulfate. Despite great variations of the H_2S inlet concentration over the day (10-50 ppm), greater than 95% removal efficiency was continuously observed. Removal of VOCs and chlorinated compounds depended on their biodegradability, but was much higher at a near neutral pH than at a low pH (pH of 1-2). Moderate fractions of common VOCs (e.g., toluene, benzene) were removed. Typical results are presented in Figure 6.

Table 6. Characteristics of the UCR biotrickling filter tested at Hyperion.

Owner and present location	University of California, Riverside/Hyperion Treatment Plant, Los Angeles, California
Builder	University of California at Riverside and Environmental Biosystems
Type of air stream	Exhaust air from the primary headworks (slip stream taken prior to chemical scrubbing)
Year of construction	1996
Packing type and volume	3.87 m^3 of COOLdeck PVC Munters 12060 structured packing.
Height and number of layers of packing	7 layers of 0.30 m on top of each other. Total bed height 2.1 m.
Biotrickling filter construction type	304 stainless steel cylindrical reactor of 1.5 m diameter and a total height of 3.35 m. The lower plenum of 0.77 m contains 800 L of recycle liquid and 0.30 m void space. The upper plenum for liquid distribution is 0.45 m high. The reactor is mounted on a trailer.
Air flow rate	650 m^3/h (380 cfm), upflow. Air flow is variable depending on the application
Empty bed residence time	21 seconds
Pressure drop	4-8 mm of water gauge
Average bed temperature	15-35 ^oC
Pollutants treated	Hydrogen sulfide: 15-70 mg/m^3 (10-50 ppm_v); VOCs and chlorinated compounds 0-150 ppb depending on the species
Biotrickling filter controls	Initial construction included 28 parameters monitored or controlled. Unit has been simplified since to include only pH control and low level switch. At Hyperion, pH control is either by purging sulfate with secondary effluent or by automatic addition of caustic soda to pH 7-8. Monitoring of various operational and performance parameters is by grab samples.
Biotrickling filter design and acceptance criterion	None. This is a feasibility study. The objective is removal of H_2S to below 1 ppm, and significant reduction of target VOCs and chlorinated compounds
Approximate investment costs	Estimated at $175,000 for the R&D unit, the cost include two reactors of 3.87 m^3, and many control and analytical devices for scientific purposes.
Approximate treatment cost per 1,000 m^3 off-gas treated	Electricity costs (recycle pump only): $0.02 per 1,000 m^3 off-gas treated; pH control cost $0-0.04 per 1,000 m^3 off-gas treated. Water costs: insignificant.
Typical performance	Reduction of H_2S down to 0.25-0.5 ppm (i.e., about 98% removal efficiency). 50-70% removal of VOCs (toluene, benzene, xylenes), removal of chlorinated compounds is currently being studied.

Figure 5. Picture of the UCR biotrickling filter installed at Hyperion Wastewater Treatment Plant in Los Angeles..

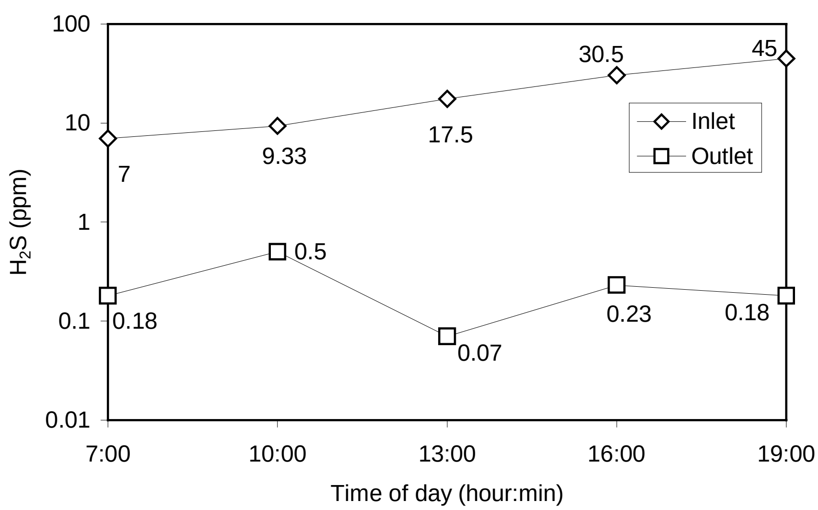

Figure 6 Typical performance of H_2S removal in the biotrickling filter. Note the fluctuating inlet concentration during the day (7 to 45 ppm). The labels show the measured H_2S concentrations in ppm_v.

H_2S and CS_2 Treatment in Monterrey, Mexico

Grupo Cydsa S.A. de C.V. is a large Mexican corporation that had in-house needs for inexpensive air pollution control, mostly for treating H_2S and CS_2 emissions from cellophane film and rayon fiber manufacturing. After evaluation of several technologies, a unique expertise was developed in the design and operation of biotrickling filters. So far, Cydsa has installed at least four full-scale biotrickling filters for the control of sulfur odors. The reactors usually use an inexpensive structured plastic packing of the type sold by Munters. They include a nutrient supply, a blow-down for the oxidized sulfur, and a pH control. The biotrickling filters have been very successful. The characteristics of one of their biotrickling filters are listed in Table 7 and a picture is shown in Figure 7.

Table 7. Characteristics of the Biocyd Celorey biotrickling filter

Owner and location	Grupo Cydsa S.A. de C.V. Ruiz Cortines Cydsa Industrial Complex, Celorey plant. Monterrey, NL. Mexico
Builder	DICOTEC (Design and Construction), a subsidiary of the Environmental Division of Grupo Cydsa.
Type of air stream	Exhaust air from a cellophane plant (viscose process).
Year of installation	1994
Packing type and volume	51 m^3 of PVC structured packing. Each layer is composed of a series of corrugated PVC sheets hot-welded together at an angle.
Height and number of layers of packing	Two sections of 2.44 m high on top of each other, separated by a 1 m air plenum. Each section is composed of 8 layers of corrugated PVC.
Biotrickling filter construction type	Cylindrical shape of 3.66 m diameter and 11.5 m total height. The bottom 3 m is used for waste gas distribution, for the foundation and as a liquid reservoir; there is a 1 m of air plenum between the two beds, and 2.5 m of space for water distribution an air exhaust above the top bed. The vessel is constructed of fiberglass reinforced plastic (FRP) coated inside and outside with resin.
Air flow rate	Waste air from 4 production lines (viscose process), total flow of 44,200 $m^3\ h^{-1}$ (26, 000 cfm), upflow
Empty bed residence time	4 – 10 seconds
Pressure drop	10 cm of water gauge of total pressure drop. 25 cm of water gauge when the maximum elimination capacity is reached.
Average bed temperature	18 – 34 ^oC
Pollutants treated	Carbon disulfide: 35 – 100 mg m^{-3}; hydrogen sulfide: 85 – 213 mg m^{-3} (60 - 155 ppm_v)
Biotrickling filter controls	Continuous monitoring (gas flow rate, recycle liquid temperature, pressure drop, recycle flow rate and pH), no automatic control is performed, except for pH, maintained between 4 and 5 using addition of a slurry of magnesium hydroxide.
Biotrickling filter design and acceptance criterion	The biotrickling filter was designed for odor control. Most of the odor comes from hydrogen sulfide, so the biotrickling filter was designed for 90% removal efficiency for H_2S. There was design criteria for carbon disulfide removal.
Approximate investment costs	\$525, 000
Approximate treatment cost per 1,000 m^3 off-gas treated	Yearly electricity and chemical costs are about \$43,000; various indirect costs (personnel, various equipment maintenance) are \$20,000. Total is \$63,000/year or about \$0.18 per 1,000 m^3 off-gas treated
Typical performance	Hydrogen sulfide is easy to degrade and usual H_2S removal efficiencies are in the range of 85 – 99 %. Carbon disulfide removal efficiency depends on the concentration of hydrogen sulfide. When the concentration of hydrogen sulfide is low, i.e., in the range of 100 – 150 mg m^{-3}, good removal of carbon disulfide is observed. At higher H_2S concentrations, the removal of CS_2 decreases. Usually, CS_2 removal ranges from 40 to 70%. The combined elimination capacity for hydrogen sulfide and carbon disulfide is usually around 310 g $m^{-3}\ h^{-1}$

Figure 7. The Biocyd Celorey biotrickling filter (Courtesy of Mauricio Acosta Grupo Cydsa S.A. de C.V.).

Odor Treatment from Cigarette Manufacturing in Berlin, Germany

M+W Zander Facility Engineering GmbH (Germany) installed a large biotrickling filter for the treatment of odors at a tobacco company in Berlin. Several air pollution control technologies were evaluated, and biotrickling filtration was selected for its cost effectiveness.

M+W Zander uses open pore polyurethane foam as a packing material (27). The foam is very light (20 kg m^{-3}), has a large interfacial area for bacterial attachment (about 600 m^2 m^{-3}), and its open pore structure results in low pressure drops. Pilot tests were performed prior to the design of the full-scale unit to ensure that odor removal was satisfactory, and that no clogging of the bed occurred within a reasonable time frame. In the full-scale biotrickling filter, a small flow of water containing nutrients is recycled intermittently over the support. The pattern adopted in this case is sprinkling 5 to 15 minutes every hour. Thus, in a sense, this biotrickling filter is operated as a biofilter for most of the time. The reactor is remotely controlled from an operator room via a modem. The characteristics of the system are reported in Table 8.

Startup of the full-scale biotrickling filter required a two-month acclimation period, after which odor removal was continuously higher than 90%. Typical inlet and outlet odor levels are 5,400 and 400 odor units, respectively and removal is consistently above 90%. Because of the low pollutant loadings and the limited supply of nutrients, clogging of the filter bed is not an issue. The pressure drop is low and stable around 2 to 4 cm of water gauge.

Table 8. Characteristics of the Reemtsma biotrickling filter. (Reprinted with permission from Devinny et al., Biofiltration for Air pollution Control, CRC-Lewis publishers, Boca Raton, FL, 1999. Copyright CRC Press, Boca Raton, Florida)

Owner and location	Reemtsma, Berlin, Germany
Builder	M+W Zander Facility Engineering GmbH, Nürnberg, Germany
Type of air stream	Cigarette production off-gas, odor treatment
Year of installation	1995
Packing type and volume	Polyurethane foam (cubes of 4 cm), total volume: 500 m^3.
Height and number of layers of packing	1 layer, 2.5 m high
Biotrickling filter construction type	6 container units.
Air flow rate	160,000 m^3 h^{-1}, downflow
Empty bed residence time	11 seconds
Pressure drop	2 - 4 cm water gauge
Average bed temperature	40 ^oC
Pollutants treated	Odors: 800 - 1,200 OU.
Biotrickling filter controls	Continuous monitoring of temperature and pressure drop, water level is controlled.
Biotrickling filter design and acceptance criterion	90% odor removal or outlet air odor lower than 100 OU.
Approximate investment costs	4.3 million DM (1995, approximately $3.05m) including ductwork cooling towers and heat exchangers.
Approximate treatment cost per 1,000 m^3 off-gas treated	Operating costs of 160,000DM per year ($93,000/yr), i.e., 0.114 DM per 1,000 m^3 off-gas treated (1997, $0.066 per 1,000 m^3 off-gas treated)
Typical performance	>90% odor removal

Odor and VOC Treatment at a Naval Air Station

As part of a technology development/technology demonstration program, Envirogen, Inc. operated a small pilot biotrickling filter and then designed a full-scale biotrickling filter for the removal of low concentrations of VOCs from contaminated air vented from wastewater treatment tanks (28). The contaminants of concern are common volatile paint solvents (ranging individually from 7-520 ppm_v) together with low concentrations (1-2 ppm_v) of H_2S resulting from sulfate reduction by anaerobic bacteria in the water tanks. The total VOC concentration in the air has relatively large fluctuations over the day, typically from 150 to 350 ppm_v (as methane equivalents).

The biotrickling filter design consists of both air and water downflow operation through two media beds in series. A computer and various data loggers are used for the monitoring and control of the reactor's operation (Table 9). The liquid recirculation rate is kept manually constant using butterfly valves. Approximately 230-380 L (60-100 gallons) of recycle liquid is removed from the system daily by a timer on a discharge valve located at the bottom of the reactor. Fresh water and nutrients are added automatically when the water level inside the system drops below a specified height. The pH is controlled automatically. At reactor startup and during initial operation, a large quantity of commercial microorganisms, cultured microbes from an in-house laboratory, and some activated sludge were used to inoculate the system. It is unknown which inoculum source has been proven to be most efficient.

Table 9. Characteristics of the Naval Air Station-North Island biotrickling filter

Owner and location	Naval Air Station-North Island (San Diego, CA)
Builder	Envirogen, Inc. (Lawrenceville, NJ)
Type of air stream	Effluent from industrial and oily wastewater treatment tanks
Year of installation	1999
Medium type, and volume of medium	Random, dump packing. Approximately 31 m^3 (1,100 ft^3).
Height and number of layers of medium	Two beds in series, each 2.1 m (7 ft.) in height. Air is downward flow.
Biotrickling filter construction type	3.0 m (10 ft.) in diameter, 9.0 m (30 ft.) tall, cylindrical in shape, cast in fiberglass resin polymer.
Air flow rate	2,970 $m^3\ h^{-1}$ (1,750 scfm)
Empty bed residence time	37 seconds
Pressure drop	12.7 cm (5 inches) total of water column across both beds
Average bed temperature	18-27 °C (65-80 °F) for recirculating water phase
Pollutants treated	Total sulfur compounds: 1 - 3 mg sulfur m^{-3} Total organic compounds: 75-175 mg carbon m^{-3} Identified compounds were: hydrogen sulfide, benzene, toluene, xylene, trimethylbenzenes, acetone, methyl ethyl ketone, methyl isobutyl ketone, methylene chloride, heptane, cyclohexane, numerous other aliphatics at lower concentrations
Biotrickling filter controls	Continuous monitoring of air and water flow, air and water temperature, pressure drop, and pH. All data is logged into a PLC for trend analysis. System conditions are monitored through the PLC. The PLC terminates system operation when alarm conditions occur (i.e. low air flow)
Biotrickling filter design and acceptance criterion	Design based on pilot-test studies on a site treating similar compounds, acceptance criterion: 80% removal of odor producing compounds
Approximate investment costs	Not available
Approximate treatment cost per 1,000 m^3 off-gas treated	Costs for water and chemicals were estimated at about $5,000 per year, i.e., $0.19 per 1,000 m^3 off-gas treated. Electricity and maintenance costs were not available but were estimated to be similar to those of a carbon adsorption system, that would otherwise be used if the biotrickling filter was not available.
Typical performance	Greater than 99 % removal of hydrogen sulfide Greater than 90 % removal of aromatics Greater than 95 % removal of ketones

Figure 8. The North Island - Naval Air Station biotrickling filter (Courtesy of Todd Webster, Envirogen Inc.).

CONCLUSIONS

There is no doubt that reducing pollutant emissions at the source should always be attempted. However zero emission is not always technically or economically feasible. For many of these cases, end-of-pipe treatment in biotrickling filters appears to be a promising alternative to conventional treatment technology. It is effective, environmentally friendly and does not have many of the drawbacks of conventional treatment technologies. The field of biotrickling filtration is maturing. The number of full-scale biotrickling filters is rapidly increasing and research makes good progress in understanding the fundamental principles of biotrickling filters. All together, this speaks for a rapid increase of the use of biotrickling filters in the 21st century.

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